Lasercom Test and Evaluation Station (LTES) development: an update

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ABSTRACT

Pre-launch integrated system characterization of a lasercom terminal's (LCT's) communications and acquisition/tracking subsystems can provide a quantitative evaluation of the terminal and afford a better rigorous assessment of the benefits of any demonstration. The lasercom test and evaluation station developed at NASA/JPL is a high quality optical system that possesses the unique capabilities required to provide laboratory measurements of the key characteristics of lasercom terminals operating over the visible and near-infrared spectral region. Over the past year LTES has been used to provide pre-flight testing of the STRV-2 lasercom terminal developed by AstroTerra Corporation of San Diego, CA, and is currently being used for testing of the Optical Communication Demonstrator (OCD) developed by NASA/JPL. Discussions of performance validation tests carried out on LTES and its diverse capabilities are reported in this paper.

Keywords: Lasercom terminal, free space optical communications, testbed, test and evaluation

1. INTRODUCTION

Recognizing the need for pre-launch characterization of lasercom terminals (LCT's) NASA/JPL initiated development of the lasercom test and evaluation station (LTES) in 1996. As conceived and subsequently designed, LTES is a high quality test-bed for making quantitative measurements of various terminal functions which serve as a bench mark for evaluating subsequent on-orbit performance of the LCT. A previous report[1] on LTES described the design requirements and goals, as well as, its optical layout and alignment procedure. Over the past year, we performed extensive tests on LTES to validate its performance. The development schedule was such that LTES was ready and available for pre-flight characterization tests of STRV-2 lasercom terminal[2] developed by AstroTerra Corporation of San Deigo, California. The tests were completed in July of 1997 prior to the delivery of the lasercom terminal for integration with other flight instruments. These test results are described in a separate report[3]. LTES is currently being used for its primary intended purpose, namely, the testing and characterization of the optical communication demonstrator[4] (OCD) developed at NASA/JPL. Preliminary results of these tests are also reported separately[5]. The experience gained so far, in testing the two LCT's indicates that LTES as built and designed allows quantitative pre-flight characterization of terminal functions. The results of the test and evaluation provide a basis for predicting on-orbit performance and information for designing the ground receiving station. In this paper we discuss tests performed to evaluate and characterize LTES performance.

2.0 THE LTES OPTICAL TRAIN AND ELECTRONIC INTERFACE

LTES is a high quality optical instrument with both receive and transmit capabilities. The received optical signal is split into power, data (eye-pattern/bit-error rate), divergence, wavelength and acquisition/tracking measuring channels. The transmitted beacon signal from LTES can be tailored to match the wavelength, polarization and modulation requirements of the LCT being tested. Underlying the optical layout of LTES is an electronic interface which allows overall command, control and data acquisition from the various channels. LTES is designed for easy transportability to spacecraft assembly or thermal-vacuum test areas. A coupling mirror assembly consisting of two 25 cm diameter high quality mirrors mounted on a specially designed adjustable rigid fixture facilitates coupling of the LCT transmit/receive axis to that of LTES. A dedicated Zygo interferometer serves as a reference source for LTES and allows ready verification of the instruments alignment.

The LTES optical train is shown in Figure 2.1. For a detailed description of the assembly and alignment see reference 1. Optical elements added over the past year and shown in Figure 2.1 are: (i) a shutter assembly in the beacon transmit channel which can be used to initiate a timed acquisition sequence and (ii) a quarter wave plate (QWP) and polarizer assembly which is used to transmit left hand or right hand circularly polarized laser light to the LCT being tested. The optical table on which LTES is assembled is enclosed in an anodized aluminum box assembled from 1/8" sheet, screwed to a sturdy frame which is secured to the table surface. A 20 cm aperture in the front panel of this enclosure allows the entry/exit of receive/transmit light. The enclosure reduces the effects of room lights and air currents in the optical train, which can degrade sensitive measurements.

Figure 2.2 shows a block diagram of the electronic interface used by LTES. A Master Interface Computer (MIC) and Acquisition Computer (AC), both Pentium PC's, are used for command, control and data acquisition operations of LTES. The COM port of the MIC is used to support an RS 422 interface which allows the control of six IMS Panther stepper motors. These stepper motors control:

(i) Neutral density filter wheels (coarse attenuators),
(ii) A worm gear driven rotating polarizer (fine attenuator)
(iii) Actuation of the flip mirror assembly.

The GPIB bus controls the following devices:

(i) Steering beam splitter assembly, Physik Instrumente Model P-173 piezo-translator and a model B-455.20 gimbal-mirror mount.
(ii) Beacon laser controller ILX Lightwave LDC-3722
(iii) Anritsu Model MA 9802A silicon photodiode sensor connected to Anritsu Model ML910B power meter.
(iv) Tektronix Model Gigabit 1400 Bit-Error Tester (BERT) Transmitter and Receiver
(v) A Burleigh Model WA-1000 wavemeter
(vi) A Tektronix TDA 820 Oscilloscope.

The MIC houses two National Instruments LAB PC+ data acquisition cards. One card is dedicated to controlling the signal recovery assembly (SRA) used for clock and data recovery. The second is used for operations related to acquisition/tracking evaluation. The Acquisition Computer has two frame grabber boards (FGB) for the divergence and acquisition channel CCD detectors. A Labview program was developed to control all the interfaces to the MIC. A graphical user interface (GUI) is presented to the experimenter to operate the different instruments. Data archiving is also controlled from the GUI. The divergence and acquisition CCD cameras are not controlled from the MIC. They have dedicated software resident in the AC. A hard wire connection, shown as trigger and strobe in Figure 2.2, between the acquisition camera FGB and the data acquisition card of the MIC allows synchronization of the acquired frame sequence with other devices. Both the computers are networked allowing access to remote printers and the internet.

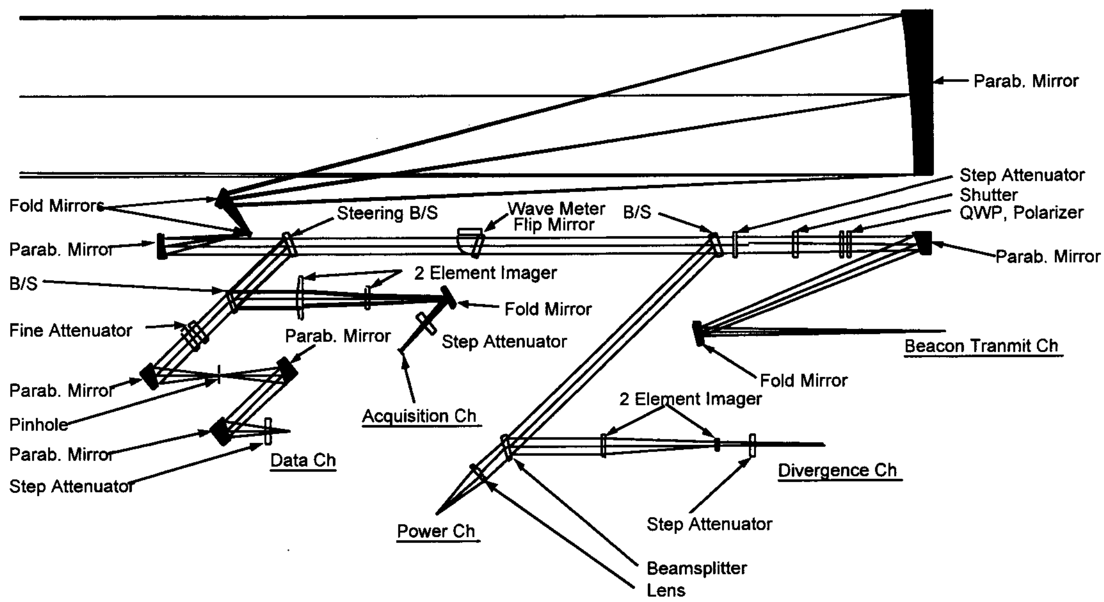


Figure 2.1 LTES optical layout showing the five receiving channels, namely, power, data, divergence, wavelength, acquisition and one beacon transmit channel.

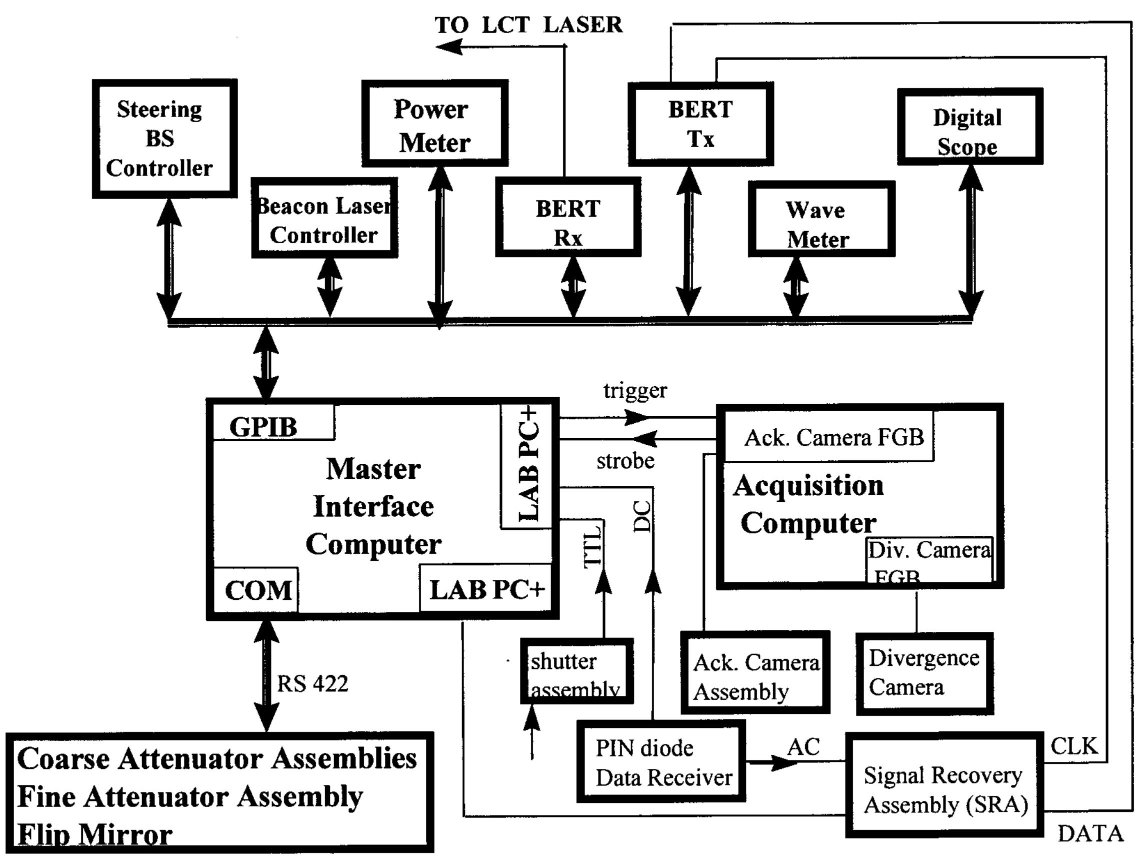


Figure 2.2 Block diagram showing the electronic interface used for command, control and data acquisition operations of LTES.

2.1 Power Channel

For LCT's such as the OCD with a 10 cm diameter transmit aperture which exceeds the receiving area of available power meters, the LTES allows a ready measurement of the emitted laser power. This is done in the power channel of LTES which measures a percentage of the total LCT light entering LTES. When calibrated at the LCT operating wavelength, the power channel measurement allows determination of the power emitted by the LCT. We have measured the power split in the LTES channels using an 840 nm laser source. The data are given in Table 2.1 and show that the measured values fall within the limits predicted. The range of expected powers predicted in the first column of Table 2.1 are based on the manufacturer specified limits of reflectance for the protected aluminum coated off-axis parabolas.

Power channel measurements can be used to infer the power in other LTES channels based upon the power split indicated by Table 2.1 This can be used, for instance, when measuring bit-error rates as a function of received power in the LTES data channel.

Table 2.1 Comparing the predicted and measured distribution of incident laser power (λ = 840+/-4 nm) in LTES

	Predicted % of total incident power based on manufacturer's reflectance values for mirrors	Measured % of total incident power 5/9/97	Measured % of total incident power 11/17/97
Power	11.1-12.9	11.4	11.8
Divergence	10.6-12.3	10.7	11.7
Acquisition	1.8-3.0	2.0	1.7
Data	4.8-5.7	5.4	5.6

2.2 Data Channel

The optical detector in the LTES data channel, which currently is a New Focus Model 1600, 1GHz bandwidth PIN diode, allows characterization of the LCT communications signal. Eye pattern analysis and/or BER measurements can be used for this purpose. The bit-error rate tester (BERT) transmitter output: a pseudo random binary sequence (PRBS), non-return to zero (NRZ), pseudo-noise (PN) data stream, represented by 2^{N-1} where N = 7, 15, 17, 20 and 23; is used to modulate the laser transmitter on the LCT under test. Figure 2.3 shows an example of a typical eye pattern measured for a EVI Inc. manufactured laser transmitter, modulated using a PN7 data stream at 500 Mbps. Such an eye pattern can be used to provide quantitative measurements[6], such as eye-height, eye-width, slope, extinction ratio[7], peak-peak jitter, duty cycle distortion and crossing percentage. These quantities determine the performance of the LCT's laser transmitter modulation circuitry. BER can also be used to determine laser transmitter performance, for instance, by comparing PN7 versus PN23 data streams. For higher data rates longer sequences better simulate real data traffic and for instance, the laser transmitter signal may be error free using PN7 but not so at PN23 modulation. This may usually be attributed to the closer spectral line spacing at higher order PN sequences thus making the clock recovery process more prone to timing jitter[8]. While using BER measurements to evaluate performance of the LCT laser transmitter caution must exercised to avoid introducing errors from the receiver or its support electronics.

Although not among the original functional requirements, the LTES data channel can also be used to evaluate the performance of the communications receiver to be used on the ground. This may involve insertion of the detector to be evaluated in LTES. The focused spot size at the LTES data channel detector was measured to be 40 μm at 632.8 nm. Thus a variety of small area, high bandwidth detectors can be accommodated. For such evaluation the laser power transmitted from the LCT to LTES, is attenuated down to levels expected at the ground receiver. Coarse and fine attenuators in LTES allow this to be achieved with a 0.2 dB resolution. Power incident on the data detector in LTES can be inferred from the power channel reading, or calculated directly by converting the data detector output. The current PIN diode detector in LTES provides a DC output voltage that can be used for the latter. Table 2.2 shows a tabulation of this PIN diodes DC and AC outputs resulting from the incidence of a laser (λ=840+/-4 nm) through variable attenuation, on the LTES data channel. This laser was modulated by a PN7 NRZ 500 Mbps data stream. The measured DC and AC signals are linear with a conversion factor of 0.153 (DC-to-AC), as determined by linear regression. Converting the DC PIN output to AC then using the specified gain (750 V/A) and responsivity at 840 nm (0.46 A/W) the peak optical power on the PIN diode can be calculated. The average power is half of this value (50% duty cycle). The last two columns of Table 2.1.1 compare the measured and calculated average optical powers, showing a very good match

Table 2.2 Showing LTES data channel detector characteristics

DC PIN (mV)	AC PIN (mV)	Measured Power (μW)	Calculated Power (μW)
29	7.1	7.46	7.40
41	8	10.5	10.46
63	12.1	16.2	16.08
84	15	21.3	21.44
106	18.6	26.7	27.05

BER measurements can be performed by feeding the AC signal directly to the BERT receiver or by making use of the signal recovery assembly (SRA) in LTES. The signal recovery Assembly (SRA) is designed to recover clock and data from a received NRZ signal. It operates at four discrete data rates of 40, 100, 325 and 400 Mbps. The SRA input is amplified by a 28 dB linear amplifier operating in the limiting mode (LG1605DXB-FLP manufactured by Lucent Technologies). The clock and data recovery (CDR) circuit uses a Comlinear CLC016 (National Semiconductors) clock and recovery chip. This device requires an ECL input and is programmable to search and lock onto one of four data rates. Frequency selection is determined by the relation:

$$R = \left[\left(\frac{1000Mbps}{f}\right) - 0.2\right] \times 1000\Omega$$

where f is the selected data rate and R is a resistor value chosen in the CLC016 circuitry. The resistors used were 24.8, 9.8, 2.87 and 2.3 KΩ corresponding to data rates of 40, 100, 325 and 400 Mbs. Table 2.3 shows the ranges around the discrete data rates at which the SRA operates.

Table 2.3

Frequency ranges over which lock with zero BER could be achieved
35-44 Mbps @ 40 Mbps
92 - 108 Mbps @ 100 Mbps
303-359 Mbps @ 325 Mbps
369-433 Mbps @ 400 Mbps

Figure 2.4 shows a comparison of the BER characteristics obtained with and without the SRA for a 100 Mbps PN7 and PN23 modulation of a EVI Inc. laser transmitter. Here BER's of 1E-12 correspond to optical power levels at and above which zero errors are registered. The SRA processed data exhibits a ~10 dB reduction in power levels required to achieve a given BER. PN23 sequences show larger BER's than PN7 sequences, probably for reasons discussed above. The results shown in Figure 2.4 are quite typical of measurements made with the current LTES data channel and were repeatable using a Hytek Inc. laser transmitter. Table 2.4 summarizes the threshold optical powers at and above which zero errors could be obtained for the two different laser transmitters operated at several different data rates. This table

corroborates ≥10 dB improvement in detection threshold with and without the SRA. This improvement we believe is due to the different input requirements of the SRA and the BERT receiver, the latter being ~10 dB higher. The ~ 5-8 μW of average optical power levels required for zero BER's with the SRA corresponds to ~3-4 mV peak-peak input signal at the SRA using the current PIN diode detector. This input level is very close to the 2mV peak-peak specified for the input level of the front end limiting amplifiers used in the SRA. Thus the optical power thresholds indicated for obtaining zero BER are limited by this input level. And once the input approaches this level the SRA can no longer perform CDR.

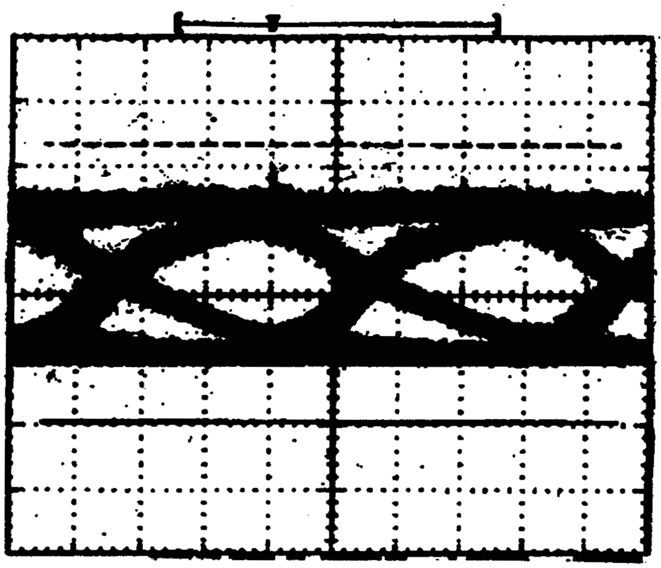


Figure 2.3 Showing the eye-diagram of a EVI Inc.manufactured laser transmitter modulated at 500 Mbps with PN7 NRZ data stream from a BERT transmitter.

The test data shown indicates that the current PIN diode detector in the LTES data channel together with the receiver electronics can operate down to optical power levels of 5-8 μW, below this level the SRA input requirements are no longer satisfied. Without the SRA the input requirements are 10 dB larger. In order to perform LTES receiver characterization using lower optical powers the detector must be changed to one with higher gain, for example, an APD with trans-impedance amplifier. Additionally a low noise high gain amplifier introduced between the detector and SRA will further extend the capability to test at lower optical powers. Such tests are planned in the future.

2.3 Divergence Channel

The LTES divergence channel uses a CCD detector in the focal plane of a two element imager lens system to measure the far-field beam intensity profile and divergence. One of the lenses of the two element imaging system is mounted on a single axis micrometer translation stage allowing fine adjustment of the lens spacing, which in turn, determines the effective focal length. Accurate knowledge of the effective focal length at the LCT operating wavelength is critical for an accurate determination of the far-field beam divergence. A Code V calculation was used to predict the lens spacing required as a function of wavelength in order to have the CCD detector at the focal plane. Table 2.5 shows the results of these calculations for a few wavelengths. The Zygo interferometer provides a nearly ideal He:Ne plane wave source at 632.8 nm. Using this as a source, the effective focal length predicted by the Code V analysis was

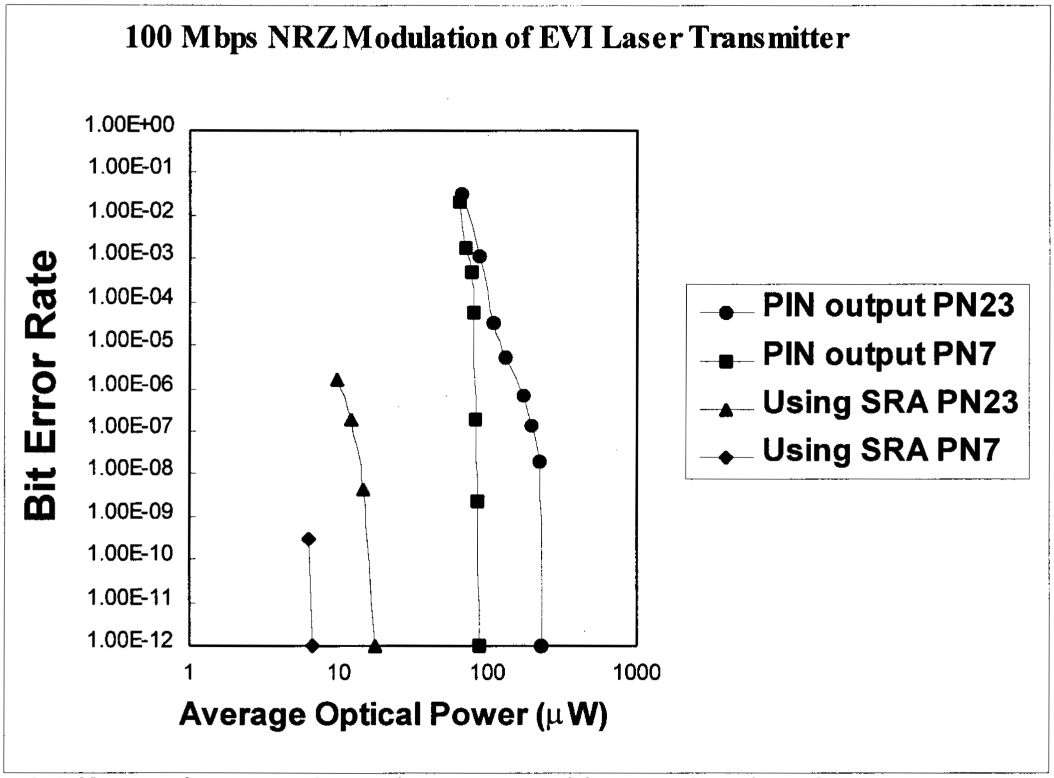


Figure 2.4 Showing the measured BER characteristics of the LTES data channel

Table 2.4 Shows incident average optical power in μW required to obtain zero BER using the Model 1601 New Focus PIN diode detector in the LTES data channel

Zero BER obtained after CDR on PIN output							Zero BER by direct measurement of PIN output					
Data Rate (Mbps)	HYTEK Inc.			EVI Laser Inc.			HYTEK Inc.			EVI Laser Inc.		
	PN 7	PN 17	PN 23	PN 7	PN 17	PN23	PN 7	PN 17	PN 23	PN 7	PN 17	PN 23
40	5.8	-	-	-	-	-	63.9	-	-	-	-	-
100	5.7	10.7	-	6.7	9.1	17.5	65.8	109	-	87.6	155.2	232.8
325	6.9	-	10.9	6.9	-	-	76	-	106.4	90.2	177.4	186.3
400	7.3	7.2	-	8.2	-	-	76.7	112	-	99	-	-
500	-	-	-	-	-	-	-	-	-	117	-	-
600	-	-	-	-	-	-	186	-	418	-	-	-

checked. The lens spacing was varied in steps while recording the average fractional energy falling inside a 243 μm aperture centered on the imaged laser spot. Maximum energy is expected for the lens spacing which coincides with the effective focal length (EFL) at 632.8 nm. The Spiricon software controlling the divergence CCD camera allows this measurement to be performed easily. Figure 2.5 shows this data plotted as percent energy inside the aperture versus EFL. A second order polynomial fit to the measured data indicates a peak at 14.8785 m, whereas, Code V analysis (Table 2.5) predicted an EFL of 14.8788 m. Agreement of the measured and predicted EFL's at 632.8 nm gives us confidence in using the predicted values for the other wavelengths where ideal sources are not readily available. The diameter of the Airy spot determined from the effective focal length is 229.5 μm and ~82% of the beams energy falls inside this diameter suggesting a Strehl of 0.95[9].

Table 2.5 Showing the Code V calculations for wavelength dependence of EFL and imager lens pair spacing in the LTES divergence channel

Wavelength (nm)	Lens Spacing (m)	Effective Focal Length (m)
632.8	0.2581879	14.8788399
780.0	0.2596724	14.9012137
810.0	0.2604794	14.9142145
844.0	0.2608116	14.9180118
852.0	0.2608866	14.9188703

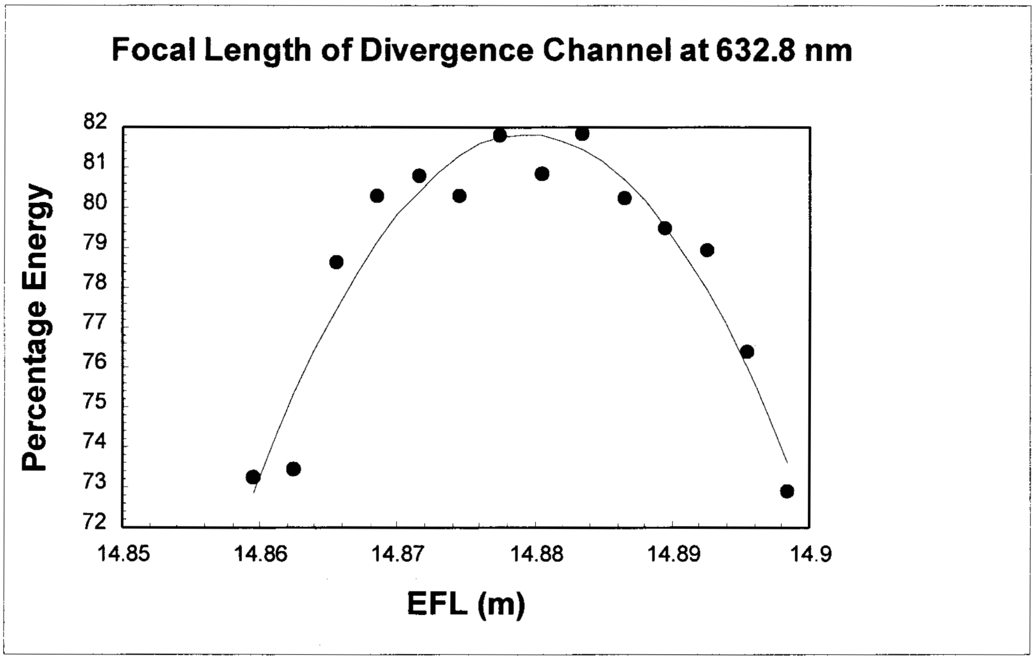
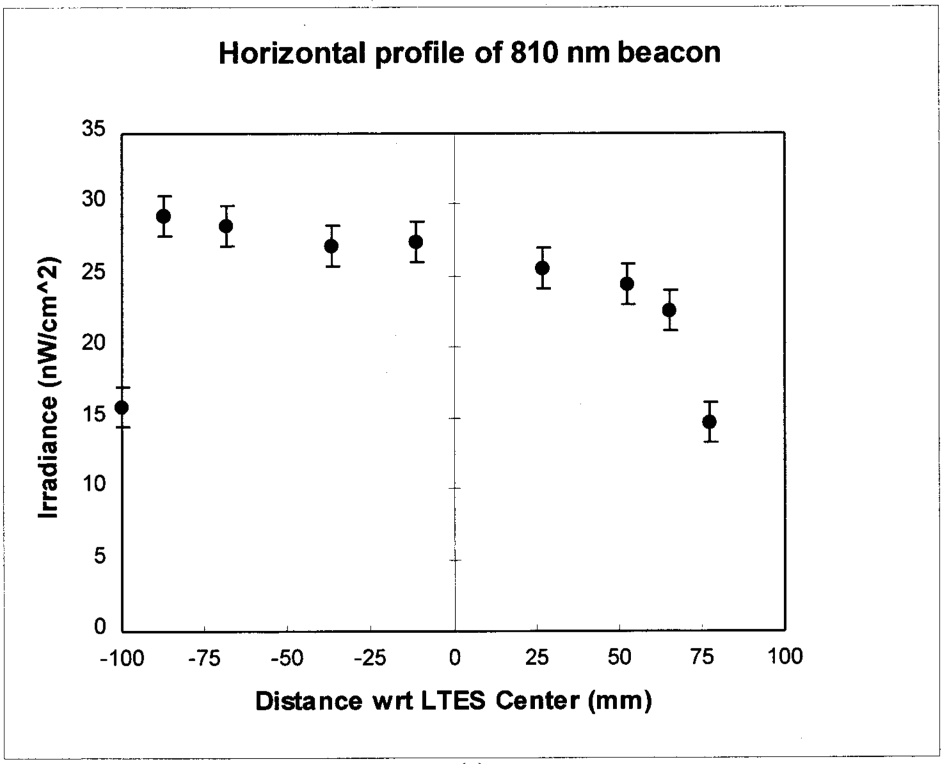


Figure 2.5 Scan of EFL to determine the maximum energy in the central lobe of the Airy disc in order to validate the focal length of the divergence channel of LTES

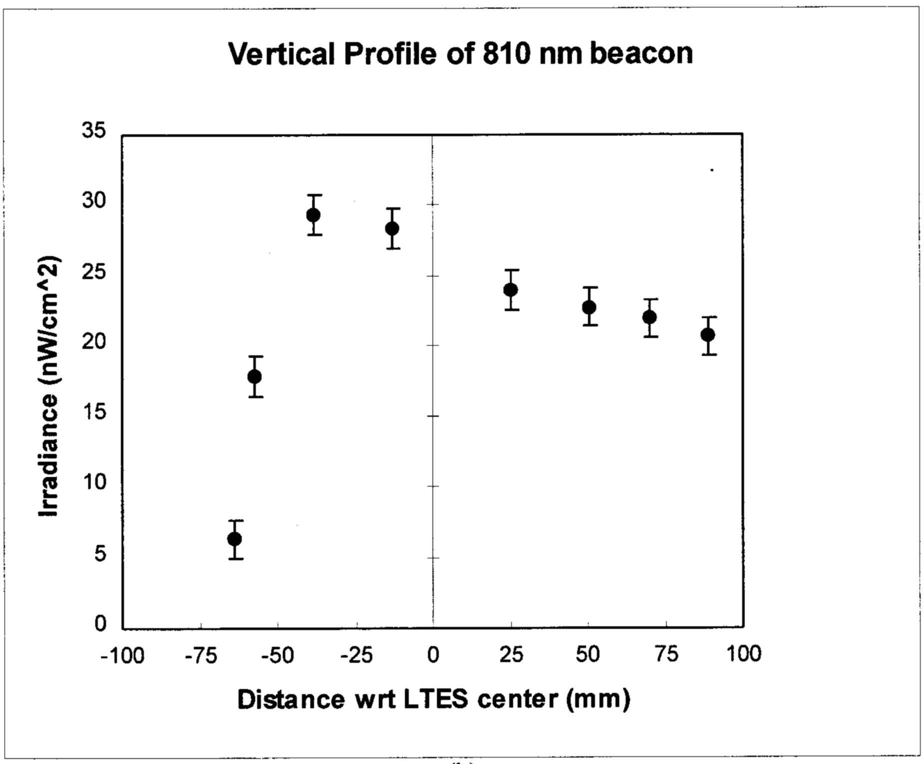
2.4 Beacon Transmit Channel

The beacon channel of LTES is used to transmit laser beams to the LCT under test. The channel was designed to accommodate the requirements of different LCT's. For example, the STRV-2 LCT, required an extremely narrow (0.02 nm) 852 nm, right hand circularly polarized (RHCP), cw beacon for testing the primary acquisition camera, while the communications avalanche photodiode (APD) detectors on the LCT required 810 nm left or right hand circularly polarized (LHCP or RHCP), high data rate (up to 622 Mbps) modulated 810 nm laser light. On the other hand, the OCD required a cw 780 nm beacon. To fulfill all of these requirements the appropriate laser light is fiber optically coupled to LTES using a single mode optical fiber. Any polarization conditioning as required for the STRV-2 LCT is then performed in the collimated portion of the transmitted beacon (see Figure 2.1).

The beacon profile exiting LTES was measured by translating a 0.71 cm^2 Anritsu Model MA 97B power sensor horizontally and vertically across the exit aperture. The beacon profile of Figure 2.6 shows that over 10 cm diameter aperture there is a maximum of 0.5 dB variation across the measured profiles. For 12 cm aperture the variation across the scans increases to 1.4 dB. The LTES design requirement called for a



(a)



(b)

Figure 2.6 The LTES (a) horizontal and (b) vertical beacon profile measured at the LTES aperture using 810 nm

0.2 dB center to edge variation across the beacon beam. In addition to a larger intensity variation the measured beacon profile also shows some asymmetry in distribution of energy. The cause for these observations we believe is apodization or non-uniform transmission of light across the aperture of the transmitted laser at the dichroic beam splitter, BS3. We plan to improve the beacon profile by replacing BS3 and avoiding the observed apodization.

2.5 Wavelength Channel

The LTES wavelength channel uses a Burleigh wavemeter for monitoring wavelengths received and transmitted by LTES. This worked well for cw beams. However, for modulated laser beams interferometric wavelength measurements became difficult. Thus the wavemeter is supplemented by a scanning monochromator for obtaining wavelength measurements and this combination has provided LTES with a very reliable and versatile wavelength measuring capability.

2.6 Acquisition Channel

The acquisition channel in LTES is designed for characterizing the acquisition and tracking functions of the LCT under test. LTES hardware and software have been developed for several anticipated experimental scenarios, such as, measuring the tracking jitter of the LCT, measuring acquisition/re-acquisition times as a function of LCT off-pointing angles and measuring point-ahead angles. The development of OCD tracking software and software to control a calibrated rotation platform which are currently underway will allow us to perform some of these tests in the near future.

The angular FOV per pixel on the acquisition CCD camera is 3.8 μrads providing an overall camera FOV of just under 1 mrad which allows tracking of the OCD transmitted laser spot over nearly the entire range of motion allowed by the fine steering mirrors (1 mrad). With the LCT transmitting laser light to LTES, the acquisition camera can record laser spot images at up to 1 KHz frame rates. The frames stored in the buffer (4096 frames) can be archived and processed for determining centroid with sub-pixel resolution. This measurement can yield an estimate of tracking jitter or point-ahead angle to within < 1μrad. The two-axis steering beam splitter in LTES allows movement of the acquired beam spot on the acquisition CCD detector while the LCT is stationary and this is useful for validating angular motion measurements.

The data channel detector signal is also used as an indicator of acquisition by LTES, of the LCT transmitted laser beam, during acquisition re-acquisition timing tests. A bore-sighted pin-hole (20,50 or 100 μm diameter) in the data channel determines the FOV (7.6, 19.25 or 38.5 μrad) over which LTES data detector can acquire.

3.0 CONCLUSION

A description of LTES in its present state of development has been provided. LTES was able to provide characterization of the STRV-2 lasercom and is currently supporting characterization of the OCD. Some future activities planned for LTES are performing on-site characterization of the OCD while it is undergoing thermal/vacuum testing. Planned upgrades to LTES include trying out new higher gain detectors in the data channel and improving the beacon channel output intensity profile to the originally intended 0.2 dB center to edge variation.

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